PAPRICAN

PPR 795

CHARACTERIZATION OF FIBRE FLOCCULATION REGIMES BY A CROWDING FACTOR

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ABSTRACT

A crowding factor, *N*, defined as the number of fibres in a spherical volume of diameter equal to the length of a fibre, has been used to characterize flocculation of fibres in water suspension. The mobility of fibres (ease of relative movement) and their uniformity of distribution were shown to change dramatically over the range $1 \leqslant N \leqslant 130$. At $N \simeq 1$, fibre mobility was high. As $N > 1$, the suspension tended to become non-uniform for fibres of high aspect ratio (length/diameter) and uniform for low aspect ratios. In the range $60 < N < 130$, fibre mobility decreased significantly. Coherent flocs of sufficient strength to withstand rupture in the flow in which they formed were found. The implications of these findings in laboratory and commercial paper-making are discussed.

KEYWORDS

FLOCCULATION, FIBERS, DISTRIBUTION, MOTION, FIBER LENGTH, FIBER DIAMETER, DISPERSIONS, CONCENTRATION, FINENESS.

RESUME

Nous avons fait appel à un facteur d'encombrement 'N', - facteur se définissant comme étant le nombre de fibres contenues dans un volume sphérique dont le diamètre est égal à la longueur d'une fibre, - pour caractériser le comportement du phénomène de floculation des fibres dans une suspension aqueuse. Nous avons observé que la mobilité des fibres (facilité du mouvement relatif) et l'uniformité de leur répartition changeaient de façon profonde dans la plage $1 \leqslant N < 130$. À un facteur $N \simeq 1$, la mobilité des fibres est élevée. Quand N était > que 1, la suspension avait tendance à devenir non uniforme dans le cas des fibres ayant un rapport d'allongement (longueur/diamètre) élevé, alors qu'elle restait uniforme dans le cas de facteurs d'allongement plus faibles. Dans la plage de $60 < N < 130$, la mobilité des fibres décroît de manière significative. Nous avons découvert des flocons agglutinés suffisamment forts pour résister à la rupture dans l'écoulement même où ils se formaient. Nous traitons dans cette communication des conséquences de ces découvertes sur la fabrication du papier en laboratoire et en usine.

1. INTRODUCTION

The tendency of fibres to flocculate into mass concentrations (flocs) has long been known to lead to poor formation in paper. The deleterious effects on paper quality makes attainment of fibre suspension uniformity a major aim in papermaking. This is generally accomplished by dispersing flocs in the headbox, or by redistribution of fibres during the drainage process.

Two aspects of a fibre suspension determine the degree to which it may lead to good formation: *uniformity* and *mobility*. A uniform suspension tends to produce good formation. Mobility, meaning the ease with which fibres can move relative to one another, also affects formation. A non-uniform suspension of mobile fibres can result in good formation because hydrodynamic forces may redistribute fibres during drainage. In contrast, such forces may not produce good formation from a non-uniform suspension of strongly immobile fibres.

A third factor also determines the degree of web uniformity produced by a draining suspension: *superposition*. The piling of fibres and flocs upon one another in itself imposes a level of uniformity in the web different from that in the suspension. Here too, however, suspension uniformity promotes web uniformity. For example, recent work by Gorres and Luner [1] has shown that superposition of flocs of low density leads to improved formation in a web.

Dilution is the principal method for increasing fibre suspension uniformity and mobility. For this reason, headbox consistencies generally fall in the range 0.5–1%. However, consistency on its own is not the sole determinant of these two factors. It has long been known, and shown quantitatively by Jokinen and Ebeling [2], that fibre length also has a sizeable effect on paper formation. Moreover, Smith [3] has shown that the role of consistency is not a simple one. He showed that under smooth drainage conditions, formation first worsened, then improved, then worsened with increasing consistency. He hypothesized that this changing effect came about from changing regimes of inter-fibre contact in the suspension.

As suggested by Smith, interfibre contact is a key factor in flocculation for it affects both the uniformity and mobility of fibres in suspension. It therefore affects what we may call the flocculation potential of pulp. This observation suggests that a parameter reflecting the level of interfibre contact in a suspension could be a useful tool for characterizing the flocculation potential of fibres. The objective of this study is to explore the use of a "crowding factor" for this purpose.

2. REVIEW OF PREVIOUS WORK

As early as 1948, Mason [4] recognized that fibre flocculation occurred primarily from mechanical interaction between fibres. Subsequent studies reinforced and elaborated upon this picture. These studies are reviewed in detail in [5]. Some key findings from them are discussed below.

In his work, Mason suggested that fibre-fibre interaction became important when a "critical concentration" was exceeded. He defined this condition as one in which there was less than one fibre in a volume of diameter equal to the length of a single fibre [4]. In more recent work [5], we extended this concept to N fibres in this volume, and called this parameter a "crowding factor". It represents the number of fibres within

the rotational sphere of influence of a single fibre. This concept is illustrated in Figure 1. Values for N can be readily calculated from the volumetric concentration of fibres, C_v, fibre length, L, and fibre diameter, d using the expression below:

$$N = \frac{2}{3} C_v \left(\frac{L}{d}\right)^2 \tag{1}$$

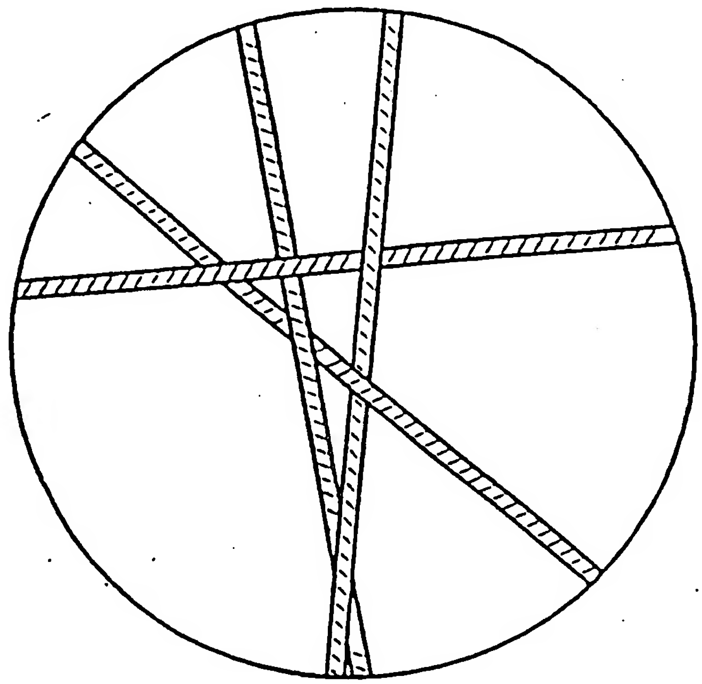

Fig. 1. The crowding factor N represents the number of fibres in the volume swept out by the length of a single fibre. It indicates the level of interfibre contact and constraint in rotational motion.

For pulp fibre suspensions, it is often more convenient to use mass consistency, C_m, and fibre coarseness, w, to compute N. Accordingly, Equation (1) may be re-expressed approximately as

$$N \simeq \frac{5 C_m L^2}{w} \tag{2}$$

where C_m is expressed in %, L in m, and w in kg/m.

For a network of randomly distributed uniform fibres, it can be shown that N is directly related to the number of contacts per fibre, n_c. Using an expression derived by Meyer and Wahren [6], simplifying for $L/d \gg 1$ (the case with pulp fibres), and then combining with Equation (1), we obtain

$$N \simeq \frac{4\pi n_c^3}{3(n_c - 1)} \tag{3}$$

Imposing the additional constraint that $n_c \gg 1$, Equation (3) simplifies to

$$N \simeq 4n_c^2 \tag{4}$$

Thus, N directly reflects the number of contacts between fibres in a random network. While this relationship is not likely to hold exactly for non-random networks, or for fibres in relative motion, it is reasonable to expect that even in these cases N represents in some measure the number of contacts between fibres.

We may now consider the behaviour of fibre suspensions at various levels of N. When $N < 1$, fibres are free to move relative to one another in translation. They occasionally collide and may remain together temporarily. As N increases, more collisions take place through translation and then eventually through rotation. When N is such that $n_c \simeq 3$, fibres on average form a continuous network between the bounding walls of the suspension. Moreover, fibres become restrained in rotation relative to one another through three-point contact. Indeed, at this condition, fibres may lock into a network in a bent configuration, and through frictional forces between fibres, create mechanical strength in the network [6]. From Equation (3), $n_c = 3$ occurs at $N \simeq 60$. Since contacts on a given fibre are unlikely to alternate on opposing sides of it, restraint in rotational motion may occur at a higher n_c, for example, $n_c = 4$ or 5. These latter values yield $N = 90$ and 130 respectively.

Based on the types of inter-fibre contact described above, fibre suspensions can be classified into different regimes. Soszynski [7] defined three such regimes as: dilute, semi-concentrated, and concentrated. He described their respective behaviour as one of chance collisions, forced collisions, and continuous contact. The nature of these regimes is summarized in Table I.

Table I
Fibre Suspension Regimes.

Regimes	*Type of Fibre Contact*	*N*
Dilute	*Chance Collision*	$N < 1$
Semi-Concentrated	*Forced Collision*	$1 < N < 60$*
Concentrated	*Continuous Contact*	$N > 60$*

* *value assigned in this study.*

We may now turn our attention from fibre contact to flocculation of fibres. In flocculation, the variation in level of fibre contact within a suspension is of key importance for it reflects the degree of non-uniformity in the suspension. Recent work by Soszynski and Kerekes [8,9] has shown that N may be useful in describing these aspects of a fibre suspension as well. In a circulating flow of nylon fibre suspensions, it was found that "coherent flocs", defined as ones having sufficient strength to withstand rupture in the flow in which they formed, appeared in a suspension at a well-defined "threshold concentration". This threshold concentration depended upon fibre length and diameter. Indeed, the condition at which coherent flocs formed could be represented by curves of nearly constant N, for a given fibre diameter, as shown in Figure 2. The influence of diameter may reflect the differing forces at each contact arising from differing fibre stiffness. Alternatively, the influence may simply be due to the fact that

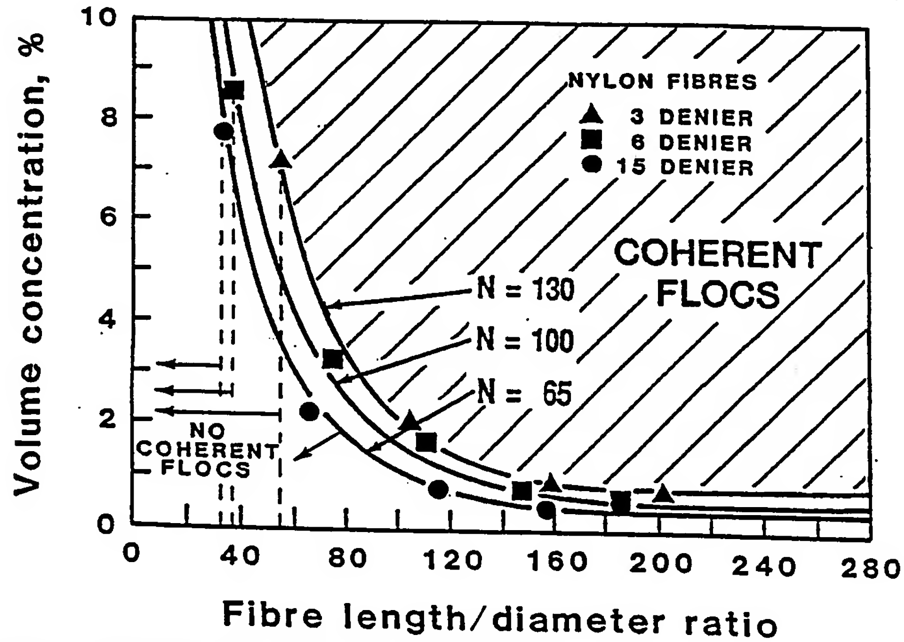

Fig. 2. Curves showing the condition at which nylon fibres formed coherent flocs in a suspension in a rotating, inclined cylinder. The experimental data for these curves are taken from [8].

physical restraint of a fibre depends upon the diameter of neighbouring fibres as well as their number. Despite this small diameter effect, however, it is apparent that to a first approximation coherent flocs first appeared in the suspension somewhere in the range $60 < N < 130$.

Based upon these observations, we may postulate the nature of fibre suspension uniformity and mobility over the range $1 < N < 130$. First, we address the question of uniformity. This property may be defined in terms of scale and intensity of flocs. For scale, we may note that conceptually N implies that flocculation begins in the sphere of influence of a single fibre, and therefore the dimension of importance for flocculation is related to fibre length, L. Indeed, it has been found that flocs are typically 1–2 fibre lengths in size [10]. Thus, we may consider the characteristic size of the non-uniformity in suspension to be related to L. To describe intensity, we may consider non-uniformity at varying levels of N, specifically flocs having a crowding factor of N_F, and zones around flocs having a lower crowding factor, N_0. For convenience, we may use N_F/N as a measure of the intensity of flocculation.

We now examine the behaviour of N_F, N_0, and N_F/N over the range $1 < N < 130$. When $N \simeq 1$, $N_F > 1$ and $N_0 = 0$. Here, flocs consist of a few fibres surrounded by zones free of fibres. When $N \simeq 60$, $N_F > 60$ and $N_0 < 60$. At this condition, fibres in flocs are inhibited in rotational motion, and may adopt mechanical strength. However, fibres in zones surrounding flocs are in a state of forced collisions, that is, relatively free to move. When N increases to a value such that $N_0 \simeq 60$, fibres in zones surrounding flocs are also in continuous contact. At this point, hydrodynamic forces act on flocs through surrounding fibres as well as through fibres within the flocs.

From the above picture, we may postulate the nature of fibre suspension uniformity and mobility with increasing N. At low N, N_F/N increases because $N_0 = 0$

in large parts of the suspension. As N increases to $N_F > 60$, coherent flocs may appear in the suspension if cyclic hydrodynamic forces are insufficient to rupture the flocs but sufficient to densify them. In this case, fibre mobility is diminished, but floc mobility (relative to other flocs) may become quite high. Indeed, the suspension can become an extremely non-uniform system of dense flocs, as found in [7]. Alternatively, fibre suspension uniformity may in some cases decrease with $N > 60$ since fibres are likely to fill voids rather than flocs. In this case, mobility of fibres is enhanced while mobility of flocs is decreased. When N increases to a level that $N_0 > 60$, there is continuous contact among fibres even in the voids. At this condition, it is reasonable to expect uniformity to worsen since hydrodynamic forces act upon flocs through fibres surrounding flocs as well as fibres within flocs and the average level of mobility of the suspension decreases.

The above postulates are supported by some experimental evidence. First, the finding that nylon fibre suspensions form coherent flocs when $60 < N < 150$ suggests that this is an important range for mechanical forces. Furthermore, the data of Smith [3] for softwood fibres, when computed on the basis of N, show that the first maximum in poor formation occurs at approximately $N = 60$, that small improvements in formation or nearly constant formation occur in the range $60 < N < 120$, and that at $N > 120$ formation begins to worsen. Lastly, perhaps the most telling evidence of the importance of the range $60 < N < 120$ comes from papermakers' use of headbox consistencies in the range 0.5–1%. As has been pointed out in earlier work [12], this is near the sediment concentration of pulp. For a softwood fibre of 3 mm length and 30 μm diameter, and typical swelling yielding $C_v = 2C_m$ [5], the consistency range 0.5 to 1% corresponds to $N = 66$ to 132.

In summary, our postulate and previous experimental evidence suggest that important changes in uniformity and mobility of fibre suspensions occurs over the range $1 < N < 150$. The aim of this experimental study is to further explore fibre suspension behaviour in this range.

3. *EXPERIMENTAL PROGRAM*

Suspensions of various nylon and pulp fibres were subjected to cyclic flows of decaying turbulence and then photographed to determine their major flocculation characteristics. The details of this procedure are described below.

3.1 Apparatus

Our tests consisted of dispersing pulp suspensions in a narrow 2-dimensional stationary channel by a grid on a plunger, and then photographing the suspension in transmitted light after cessation of plunger motion. The apparatus is illustrated in Figure 3, and shown in Figure 4. The glass channel was 243 mm wide, 457 mm high and 23 mm deep. Fields of decaying turbulence were imposed in it by a grid at the end of a reciprocating plunger moving at 0.5 m/s. The grid consisted of a row of 18 mm diameter cylinders with 18 mm spacing between them. A plexiglas plate was secured to the upper side of the grid, parallel to the wall of the cylinder to give a channel depth of 9 mm on the downstroke. Thus, on the downstroke, the channel depth was approximately one floc in size.

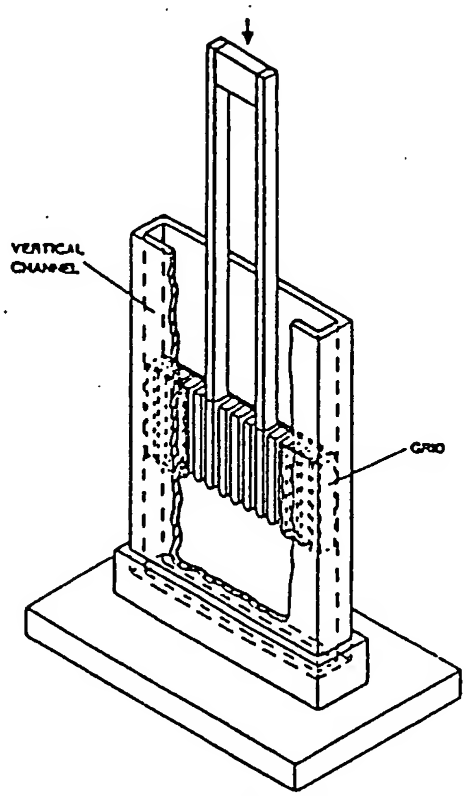

Fig. 3. Diagram showing the concept of a grid pulled through a verticle, narrow stationary channel.

The test procedure consisted of agitating the suspension by reciprocating plunger motion, stopping the plunger in the down position, allowing the turbulence to decay to a stationary state (approx. 15 s) and then photographing the suspension. The suspension was photographed under transmitted light using an Olympus OM-2 35 mm camera, with back illumination from four 300 watt quartz bulbs shining through a light diffuser. A viewing section of approximately 150 mm by 100 mm, framed by black cardboard to minimize glare, was employed. ASA 160 Tungsten colour film and ASA 125 Ilford FP4 film were used in the tests.

3.2 Fibres Tested

Three wood species and two types of nylon fibres were tested in this study. The wood fibres were kraft-pulped Douglas Fir, Western Red Cedar, and Aspen. Their length and coarseness were measured in a Kajaani FS-100 fibre analyzer and are shown in Table 2. The nylon fibres were 1 mm and 3 mm length, and 15 denier (44 μm) in diameter. The nylon fibres were washed and prepared according to the procedure outlined in [7].

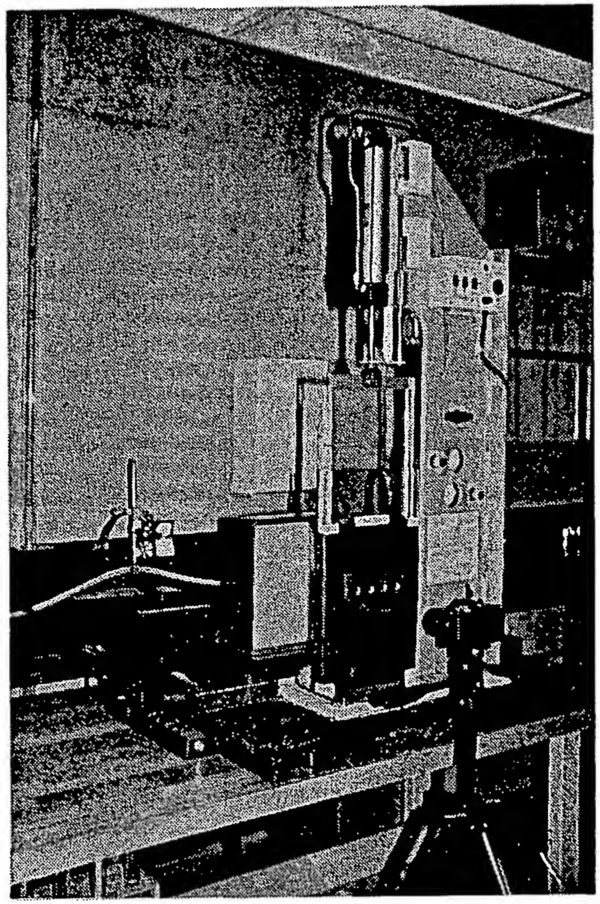

Fig. 4(a). Photograph of decaying shear channel in which pulp suspensions were agitated by a grid secured to a vertical plunger driven by compressed air.

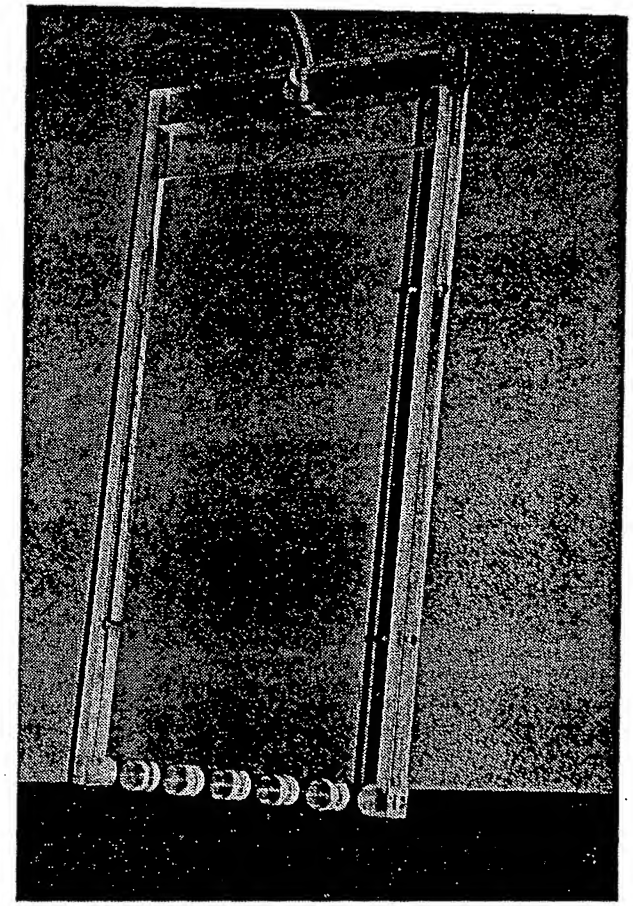

Fig. 4(b). Vertical movement of the row of cylinders located at the bottom of the plunger creates decaying turbulence in the suspension. The plexiglas plate above the cylinders decreases the depth of the channel to about the size of one floc when the plunger is stopped at the end of a downstroke.

Table II
Physical Properties of Fibres.

	Length mm	Diameter 10^{-6}m	L/d	Density g/cm³	Fibre Coarseness mg/100 m
Nylon	1	44	23	1.13	166.7
	3	44	68	1.13	166.7
Douglas Fir	2.7	40* (35–45)	67.3	0.545	25
Western Red Cedar	2.5	35* (30–40)	70.6	0.368	12.3
Aspen	0.83	18* (10–27)	46.1	0.433	10.8

* *Data from Isenberg [11]; ( ) shows range.*

4. RESULTS AND DISCUSSION

Photographs of the fibre suspensions along with their C_m and N values are shown in Figures 5–8.

Figures 5 and 6 illustrate the effect of increasing concentration in suspensions of nylon fibres. For the 3 mm fibre shown in Figure 5, increasing N leads to strong flocculation at $C_m = 3\%$ ($N = 84$). At $C_m = 4\%$ ($N = 112$), coherent flocs appear. These flocs do not disperse and are similar to those observed in recirculating flow tests reported in [8,9]. Indeed, the coherent flocs form at the same C_m in both cases. Thus, in both tests, conditions are such that flocs may adopt sufficient mechanical strength to withstand rupture in the shear imposed by the flow. Once such coherent flocs form, cyclic hydrodynamic forces tend to densify the flocs.

In contrast to the 3 mm nylon fibre, the 1 mm nylon fibre suspension shows increasing uniformity with increasing consistency, as is evident in Figure 6. Indeed, at $C_m = 2\%$ the suspension of 1 mm fibres is virtually uniform. This same fibre did not form coherent flocs in recirculating flow, even at very high concentrations.

The startling contrast between the 1 mm and 3 mm nylon fibres is explained by their representative N values. At $C_m = 2\%$, the 1 mm nylon fibre suspension had $N = 7$. In contrast, at $C_m = 1\%$ the 3 mm nylon fibres had $N = 28$ and at $C_m = 4\%$, $N = 112$. In summary, the length to diameter ratio (L/d) of the 1 mm fibres is too small for fibres to interlock to form mechanical strength, and therefore the suspension tends to remain uniform.

Suspensions of Douglas Fir fibres are shown in Figure 7. At $C_m = 0.017\%$ (the level of standard sheet making), fibres are clearly not linked into a network. This is expected because $N = 3$. However, as consistency increases, flocculation appears. At $C_m = 0.1\%$ ($N = 16$) loose flocs appear, and at $C_m = 0.5\%$ ($N = 75$), distinct flocs appear, with voids between flocs. At $C_m = 1\%$ ($N = 151$) some very dense flocs appear in the suspension which do not appear to rupture. As in the case of the 3 mm nylon fibres, it appears that coherent flocs form and continued action of the plunger merely serves to consolidate and strengthen the flocs.

Figure 8 shows suspensions of Cedar fibres. Here too, at $C_m = 0.017\%$ ($N = 4.4$), fibres are not linked into a network. At $C_m = 0.1\%$ ($N = 26$) some loose flocs appear, and at $C_m = 0.3\%$ ($N = 78$) some distinct flocs appear. At $C_m = 0.5\%$ ($N = 130$) dense flocs appear that do not rupture.

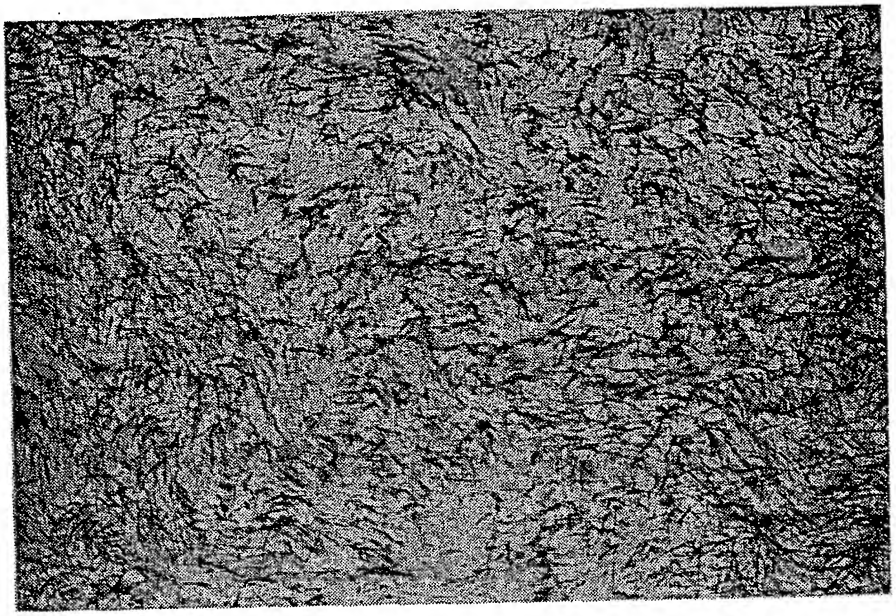

Fig. 5(a). 3mm Nylon Fibres; C_m = 0.1%; N = 3.

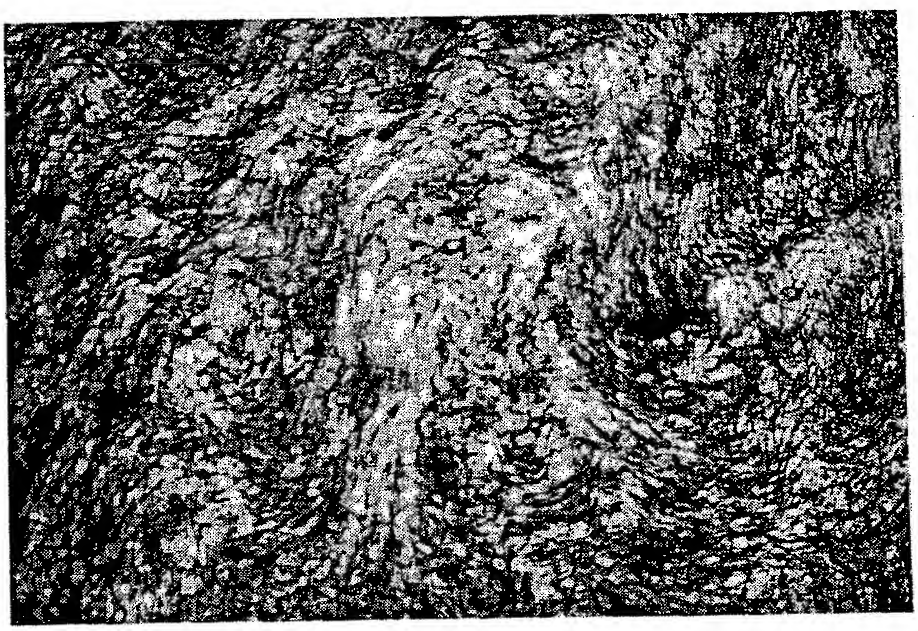

Fig. 5(b). 3mm Nylon Fibres; C_m = 1.0%; N = 28.

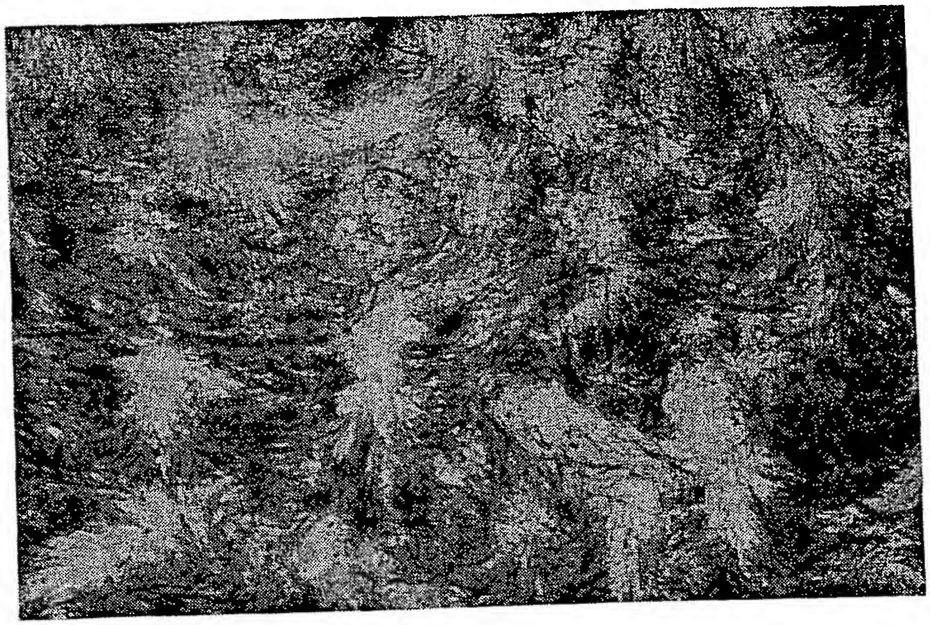

Fig. 5(c). 3mm Nylon Fibres; C_m = 3.0%; N = 84.

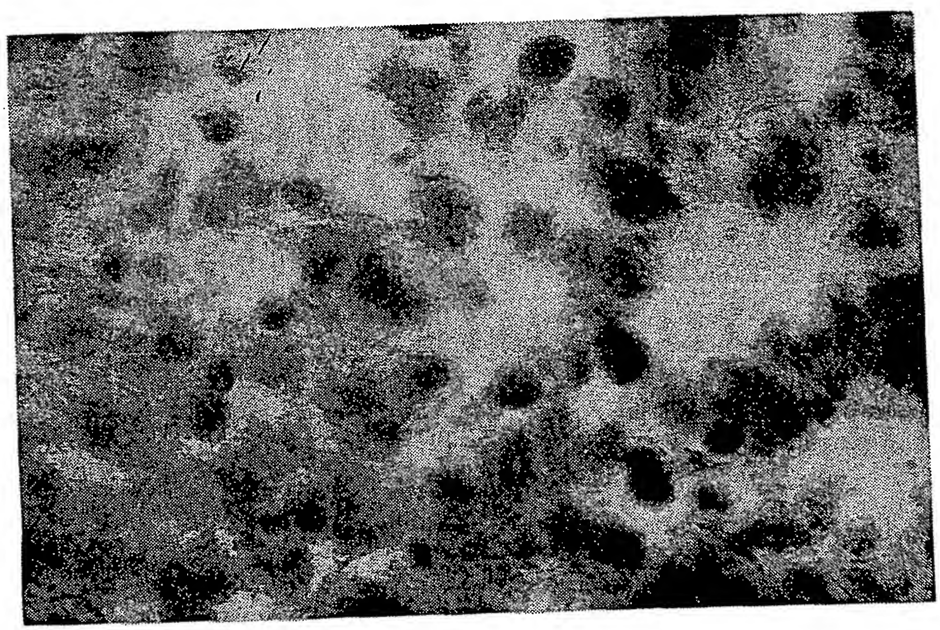

Fig. 5(d). 3mm Nylon Fibres; C_m = 4.0%; N = 112.

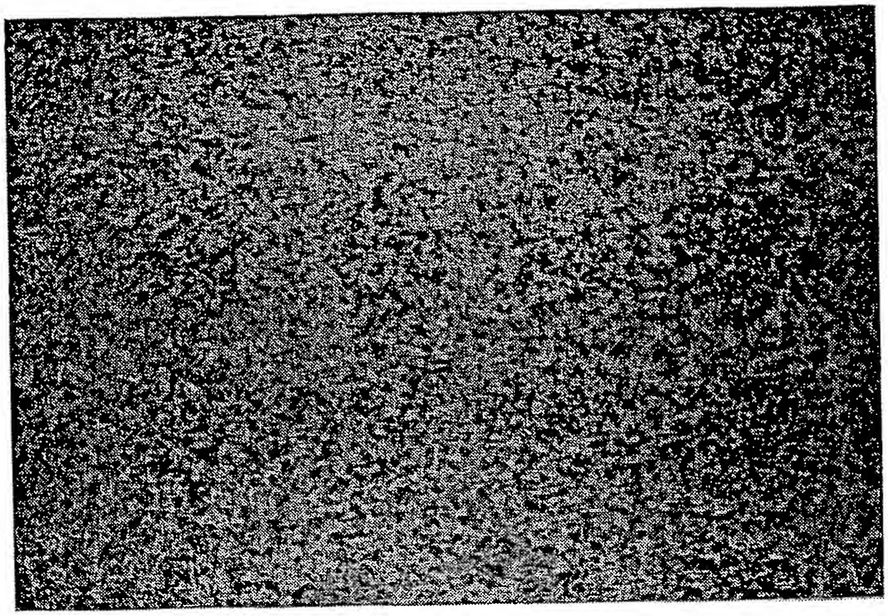

Fig. 6(a). 1mm Nylon Fibres; $C_m = 0.1\%$; $N = 31$.

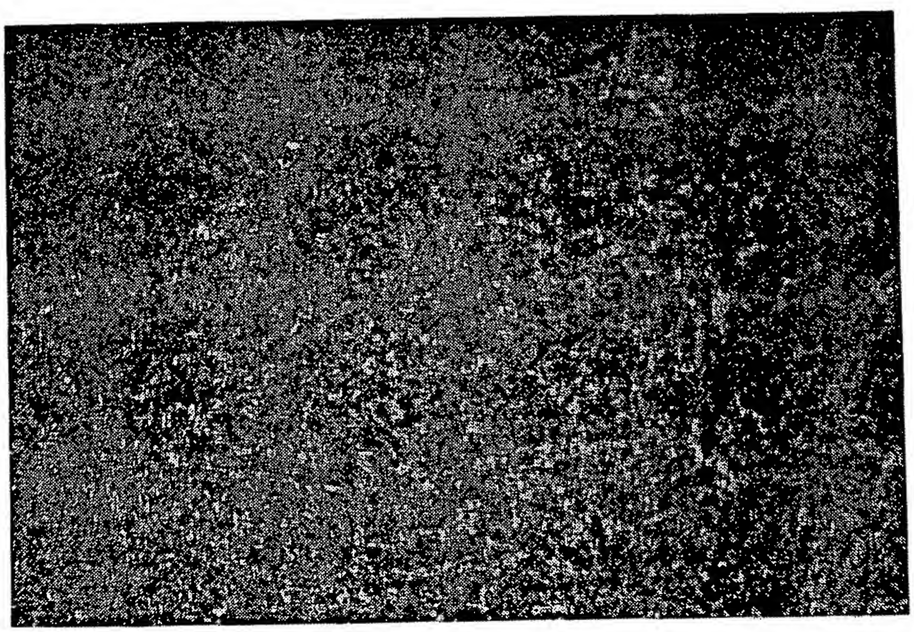

Fig. 6(b). 1mm Nylon Fibres; $C_m = 0.5\%$; $N = 1.6$

0.05%

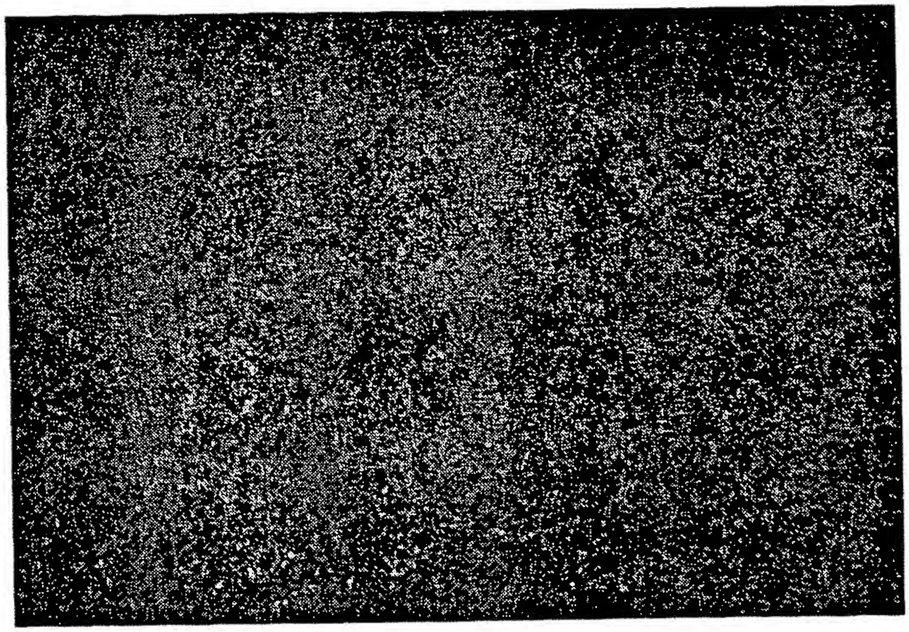

Fig. 6(c). 1mm Nylon Fibres; C_m = 1.0%; N = 3.1

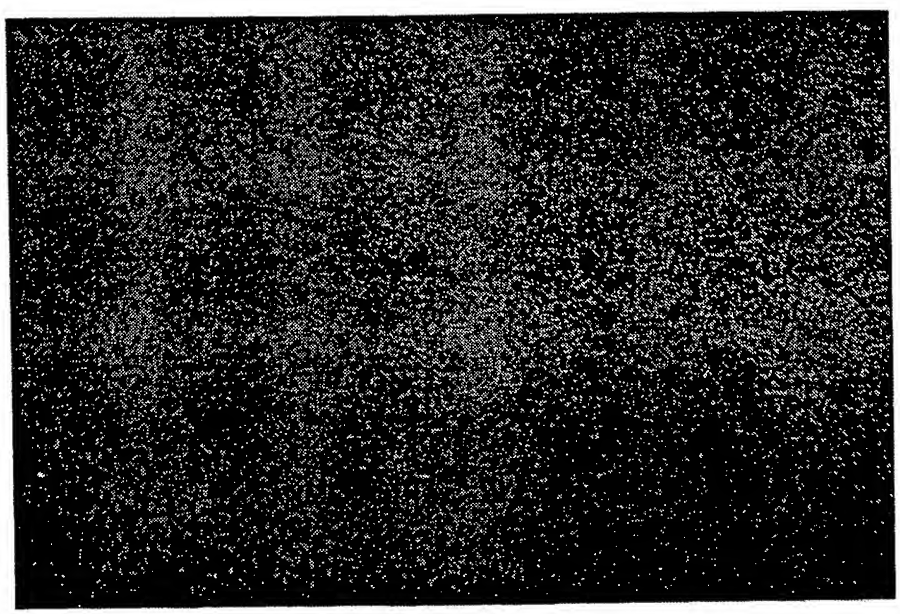

Fig. 6(d). 1mm Nylon Fibres; C_m = 2.0%; N = 7.

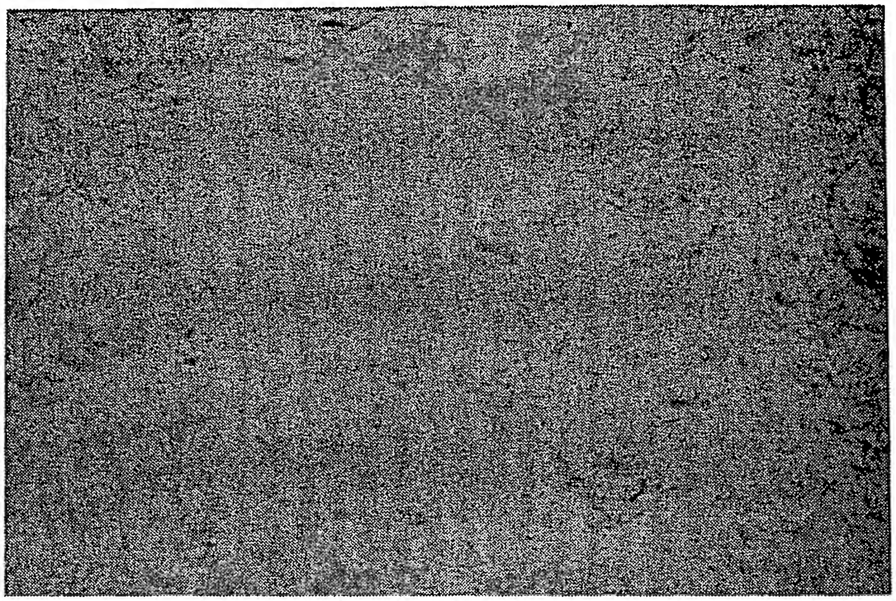

Fig. 7(a). Douglas Fir; C_m = 0.017%; N = 2.7.

Fig. 7(b). Douglas Fir; C_m = 0.1%; N = 16.

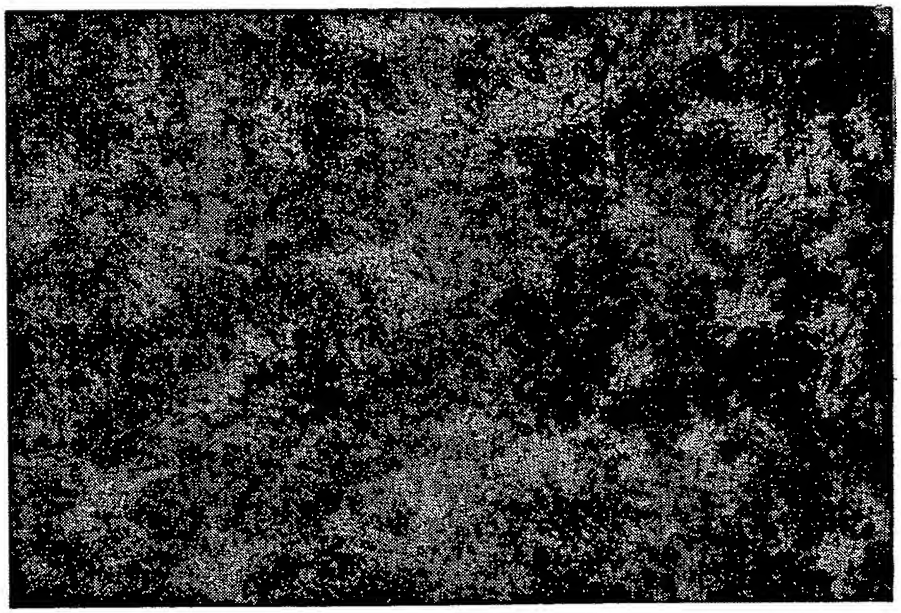

Fig. 7(c). Douglas Fir; C_m = 0.5%; N = 75.

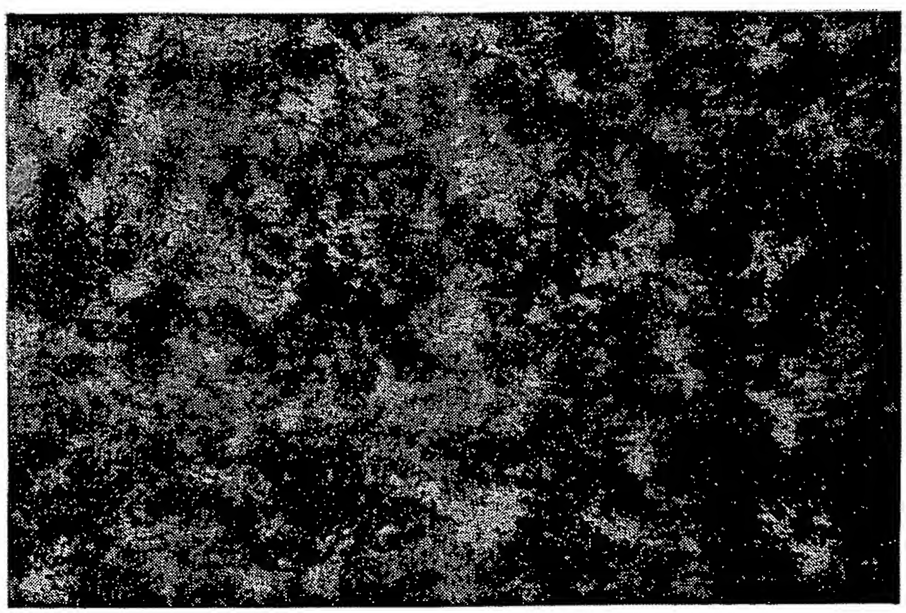

Fig. 7(d). Douglas Fir; C_m = 1.0%; N = 151.

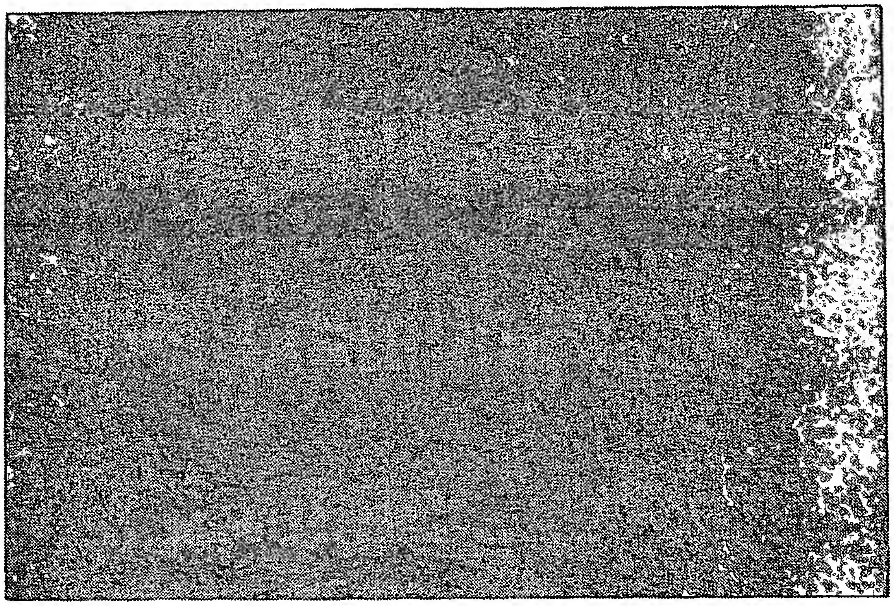

Fig. 8(a). Western Red Cedar; C_∞ = 0.017%; N = 4.4.

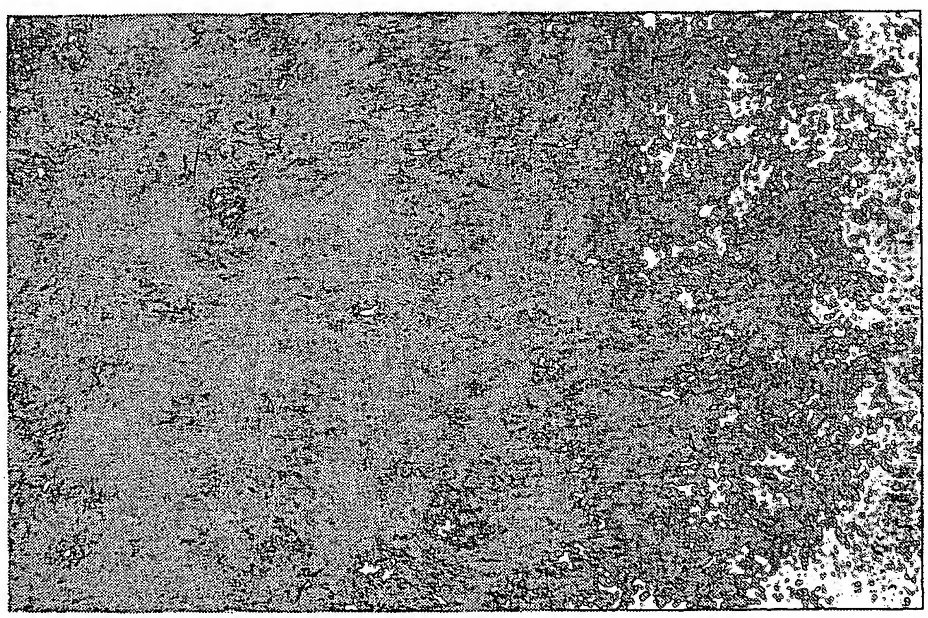

Fig. 8(b). Western Red Cedar; C_∞ = 0.1%; N = 26.

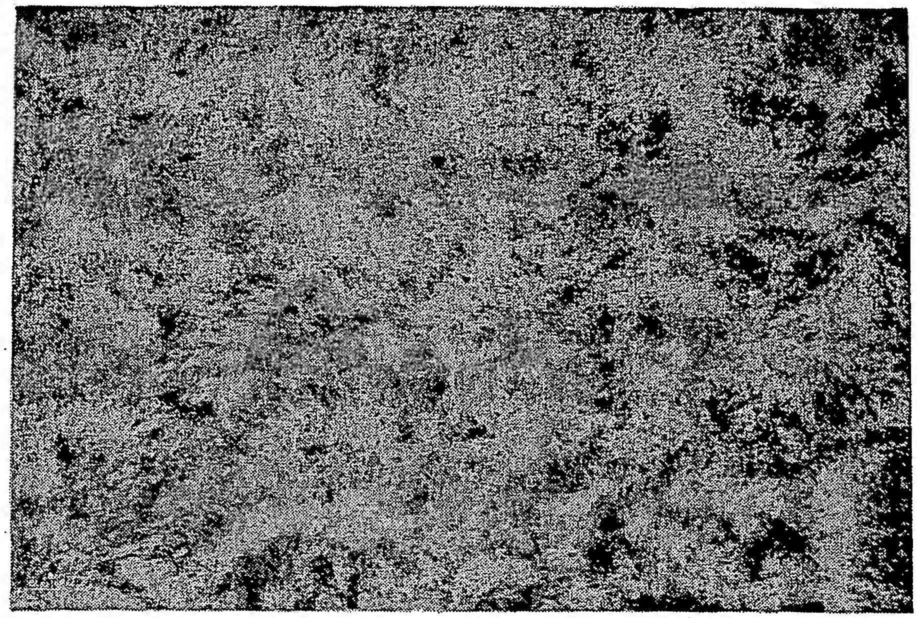

Fig. 8(c). Western Red Cedar; C_m = 0.3%; N = 78.

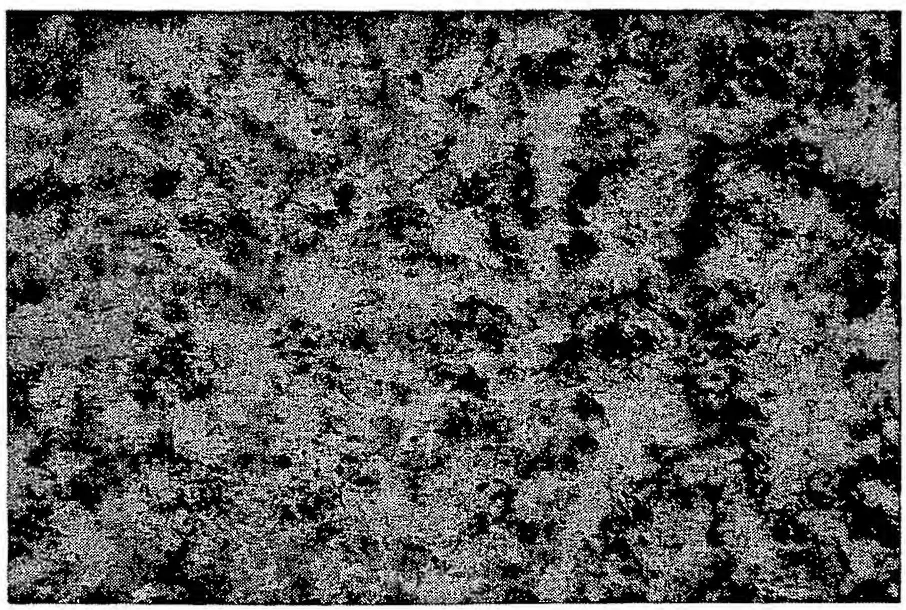

Fig. 8(d). Western Red Cedar; C_m = 0.5%; N = 130.

Suspensions of Aspen fibres are shown in Figure 9. At C_m = 0.5% (N = 17), some flocs appear in the suspension. At C_m = 1% (N = 34), the suspension appears, if anything, to grow somewhat more uniform. This behaviour is similar in many respects to the behaviour of 1 mm nylon fibres described earlier. Indeed, the L/d of this species (46) falls in the region in which coherent flocs did not form in Figure 2.

These findings have some important implications in papermaking. First, the standard handsheet procedure employs fibre suspensions at C_m = 0.017%, that is a condition at which $N \simeq 1$. In this range fibres only begin to have forced collisions. The fibres are very mobile. Even if flocs form, they are loose weak structures. Accordingly, fibre flocculation in the suspension is not a major factor in sheets produced from the test. While this is probably the intent of the test, it should be noted that by forming sheets at this condition, a major property of pulp fibres — their tendency to flocculate in suspension — has been eliminated as a factor in assessing pulp quality.

When N is small ($1 < N < 60$), there appear to be two possible types of behaviour with increasing N. If L/d is small ($L/d < 50$), the suspension tends toward uniformity with increasing concentration. On the other hand, if L/d is large, loose unconnected flocs appear in the suspension with increasing concentration. The suspension in this latter case is quite non-uniform; however, because fibre mobility is relatively high, these flocs are easily dispersed by hydrodynamic forces.

In the range $60 < N < 130$, fibre mobility decreases significantly. Flocs in the suspension adopt mechanical strength and therefore become difficult to disperse. In papermaking, this means higher shear forces are required to disperse flocs, at levels perhaps not attained in some headboxes. Suspension uniformity varies over this range. In the lower end, it may improve as additional fibres fill voids. However, as the number of fibres increases in these zones at the upper end of this range, poorer uniformity may result from densification of flocs forced by continuous fibre contact rather than fibre collisions.

5. CONCLUDING REMARKS

Our findings suggest that a "crowding factor" based upon the number of fibres in a volume swept out by the length of a single fibre is a useful parameter to characterize regimes of fibre flocculation in which suspension mobility and uniformity change significantly. The factor accounts for some of the major effects of consistency, fibre geometry, and coarseness.

It should be noted that the crowding factor does not in itself yield what might be called the "flocculation tendency" of a pulp. This is also determined by other factors, such as the degree to which fibres can cohere for a given number of contacts between fibres. The crowding factor represents only the number of contacts. We shall address the issue of flocculation tendency in future work.

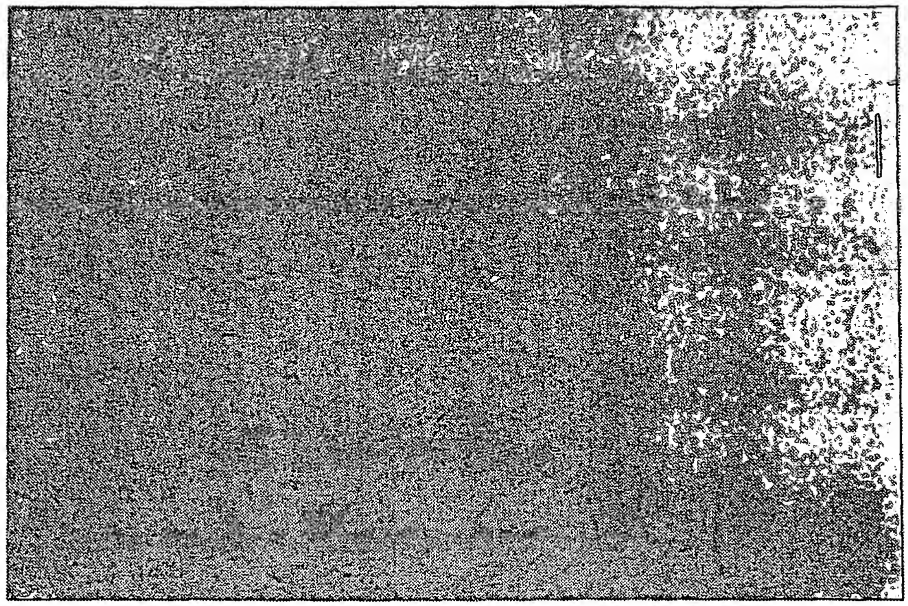

Fig. 9(a). Aspen; C_m = 0.017%; N = 0.6.

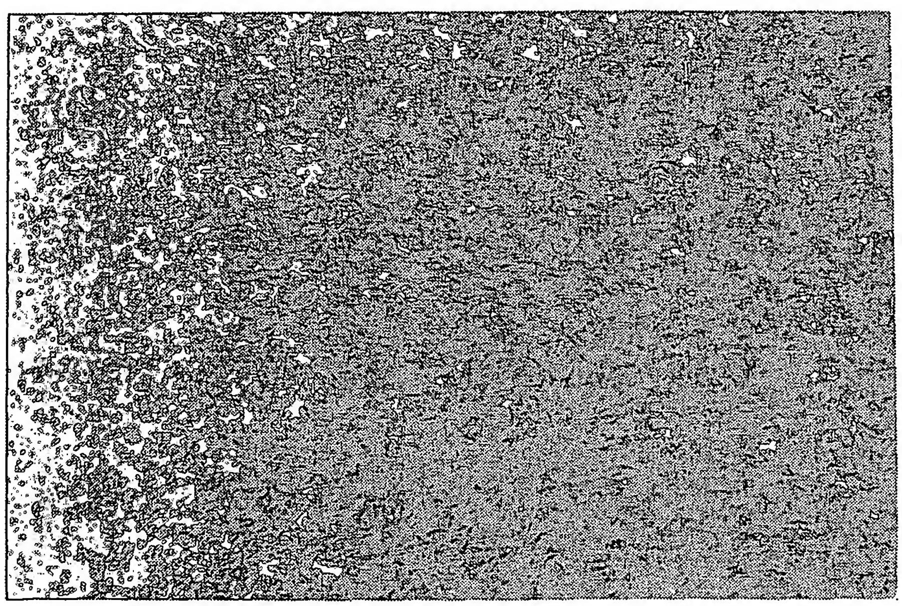

Fig. 9(b). Aspen; C_m = 0.1%; N = 3.4.

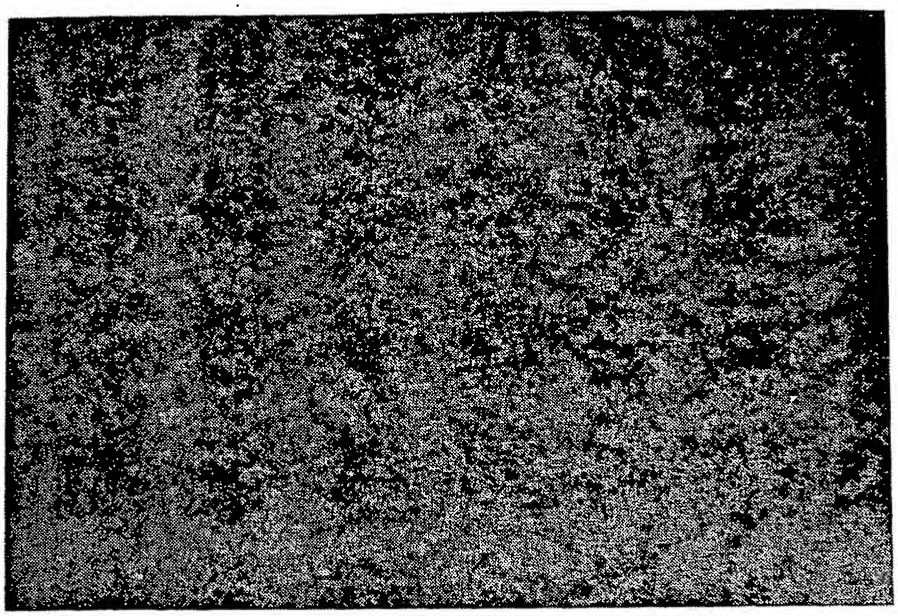

Fig. 9(c). Aspen; C_m = 0.5%; N = 17.

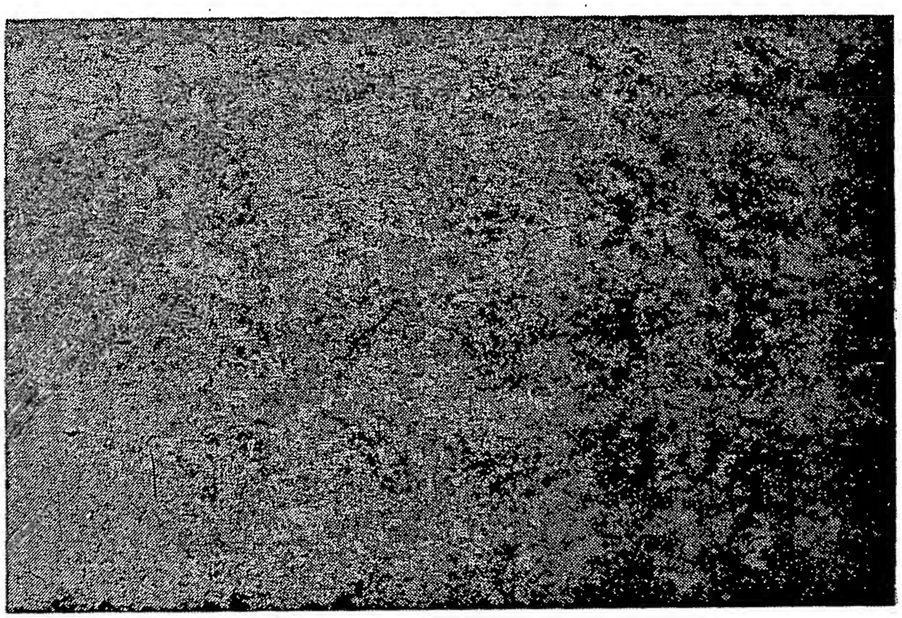

Fig. 9(d). Aspen; C_m = 1.0%; N = 34.

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